ATTENUATION OF REPEATED SHOCK WAVES IN TUBES

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by

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ABSTRACT

The field of attenuation of repeated shock waves bears much investigation. In this field there are theories to explain the attenuation of infinite plane waves and infinitesimal waves but no suitable theoretical explanation of the attenuation of finite repeated waves. Professor I. Rudnick has proposed an equation to explain these phenomena but has failed to obtain experimental proof of its validity. Some work has been done in this field by other investigators. This investigation was undertaken to determine the validity of the theory over a series of tubes of various diameters and at several frequencies.

This investigation has failed to substantiate the validity of the equation but has instead produced results which support the previous work done in the field which tend to negate the theory.

The investigators wish to express their thanks to Professors H. Medwin and C. B. Wilson, Jr. of the U. S. Naval Postgraduate School for their encouragement and helpful suggestions during the conduct of this investigation.

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1. Introduction

Shock waves in gases are characterized by a pressure discontinuity at the shock front. In the field of gas dynamics, three distinct types of shock waves are observed: (1) Standing shock waves such as are generated from the leading edge of an aircraft flying at supersonic speeds, (2) single traveling shock waves which are generated by an almost instantaneous change in pressure differences such as occur in an atomic explosion, and (3) repeated traveling shock waves which are generated by intense sound waves. Much investigation has been undertaken for standing shock waves and the theory is rather complete. The Rankine-Hugoniot relations sufficiently describe the single traveling shock wave at the present time. Theory exists for the infinite plane repeated shock waves but an adequate theory does not exist for finite plane repeated shock waves. This investigation is confined to the attenuation of finite plane repeated shock waves in tubes.

Shock wave research is important to ascertain basic data and methods available for dissipating exceptionally high noise levels without incurring large back pressure to engine exhaust, etc. This is of particular importance in this jet age.

2. Characteristics of repeated shock waves.

Both single shock waves and repeated shock waves can be generated under controlled laboratory conditions. The usual method for generating a single shock wave is by the rupture of a diaphram separating gases at two different pressures. This shock wave propogates with a velocity greater than sound and is the familiar type generated by explosions, atomic blasts, etc. Figure 1 depicts this type of shock wave.

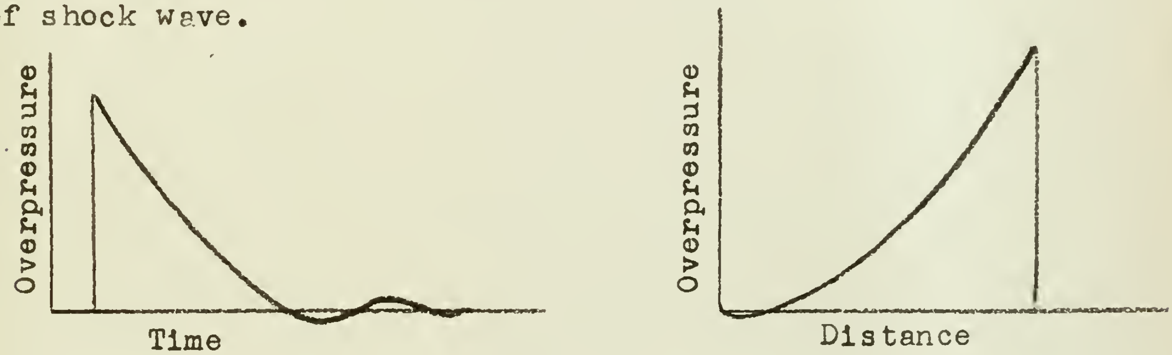


Fig. #1

Repeated shock waves travel with the normal speed of sound and have a saw-tooth wave form which is stable except for a gradual amplitude attenuation due to absorption processes.[1] The shock front is formed by the distortion of a high amplitude progressive sound wave (whose initial pressure variation is in the form of a sine function) due to the peak overtaking the trough. As the crest of the sound wave travels at a velocity equal to the sum of the particle velocity and the velocity of sound and the trough travels at

[1]G. Werth, "Attenuation of Repeated Shock Waves in Tubes", UCLA 1953

a velocity less than the velocity of sound, the gradient increases on the leading front of each wave and decreases on the trailing front and the shock is formed. See Figs. 2a, b & c below.

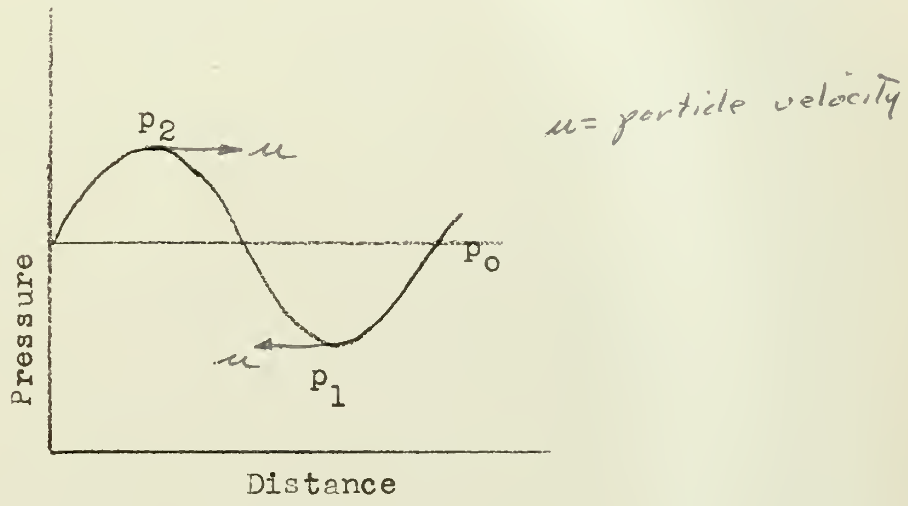


Fig 2a High Amplitude Sound Wave

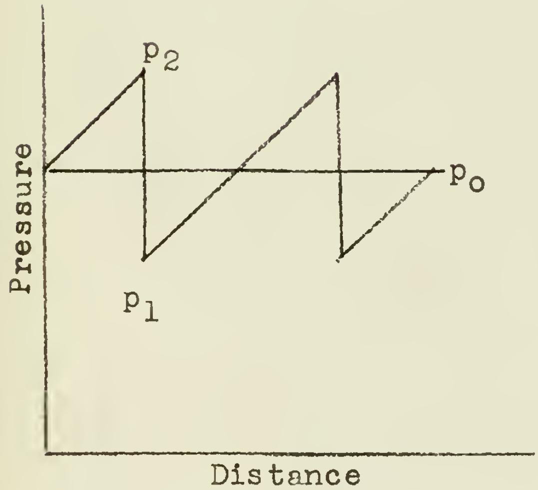


Fig 2b Shock Wave Variation of Pressure with Distance

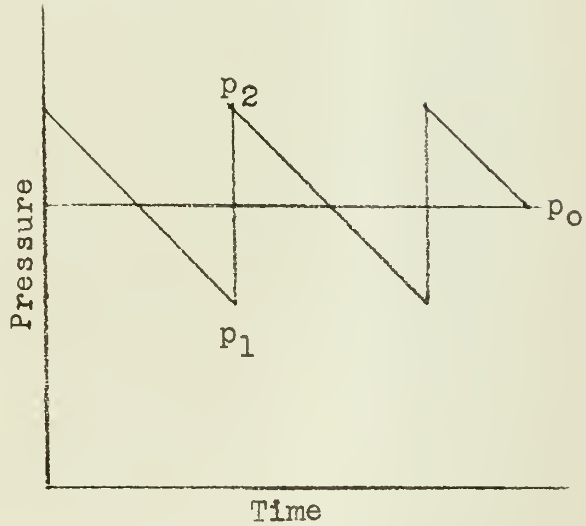


Fig 2c Shock Wave Variation of Pressure with Time

3. Attenuation of repeated shock waves theory.

Professor I. Rudnick of UCLA, in his Technical Report to the U. S. Navy [1] has developed the best formula to date explaining the attenuation of repeated shock waves. By using the Rankine-Hugoniot relations and equating the increase in entropy across a shock front with the rate of energy decrease, he derived the following formula:

$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{\gamma+1}{2\gamma\lambda}(x - x_0)$$

where $\delta = \dfrac{p_2 - p_1}{p_1}$ λ = wave length

x = distance from sound source

$\gamma = C_p/C_v$ (ratio of Specific Heats)

The above formula assumes a saw tooth wave form and is one dimensional implying the infinite plane wave. The formula also ignores the effect of tube boundaries. No adequate theoretical treatment for finite amplitude or repeated shock waves in tubes exists. The best available for the former is Kirchoff's infinitesimal solution,[2] where

$$\delta = \delta_0 e^{\alpha_w (x - x_0)}$$

$$\alpha_w = \frac{1}{\delta}\frac{d}{dx}(\delta) = (\pi\mu)^{\frac{1}{2}}\left[\frac{1}{\gamma^{\frac{1}{2}}} + \frac{\gamma-1}{\gamma}\left(\frac{k}{C_v\mu}\right)^{\frac{1}{2}}\right]\frac{1}{r}\left(\frac{f}{\rho}\right)^{\frac{1}{2}}$$

and μ = coefficient of viscosity

f = frequency

k = thermal conductivity

r = radius of tube

[2] J. Acoustical Soc of America, Vol 26, No 1, Jan 1954, p. 61

Wilson and Bies in a similar report to the Navy [2] used Rudnick's basic equation which combined the tube and the infinite plane solutions and accounted for the losses in the tube walls[3] in the formula:

$$1/\delta - 1/\delta_0 = a_1 x + 1/\delta_{ave.} \quad a_2 x$$

where $1/\delta_{ave} = \frac{1}{2}(1/\delta + 1/\delta_0)$

$a_1 = \dfrac{1+\gamma}{2\gamma\lambda}$ (attenuation at shock front)

$a_2 = \dfrac{170\sqrt{f\nu'}}{dc}$ (additional losses at the tube walls)

c = velocity of sound

x = distance from sound source

γ = C_p/C_v (ratio of specific heats which for air is 1.4)

λ = Wave length

d = diameter of pipe

f = frequency

P_2 = peak pressure

P_1 = trough pressure

The quantity ν' is a function of the kinematic coefficient of viscosity and the thermometric conductivity coefficient for air.[4] Wilson and Bies [2] found that the term involving a_2 is at most only 5% of the term involving a_1 for their experiment.

[3]Wilson and Bies Technical Notes Report 79, Soundrive Engine Company, Los Angeles, California, 1953, pg 15

[4]Rayleigh, "Theory of Sound", Dover Publications, 1945, Vol II, pp 323-325

4. Previous Investigations

Previous investigations of the attenuation of shock waves in tubes have been carried out in three reported cases. The first such investigation was by Rudnick and Leonard under a contract by Soundrive Engine Company with the Office of Naval Research and reported upon in 1953 [3]. The investigation involved the attenuation of extremely high amplitude sound pressures generated by a siren with the air supply furnished by utilizing two Packard-Merlin aircraft engine superchargers. Rudnick and Leonard used a 60 foot long pipe with a ten inch inside diameter for the investigation and studied frequencies of 20-200 cycles per second. Using the formula

$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{\gamma+1}{2\gamma\lambda}(x - x_0)$$

a graph was plotted of $1/\delta$ vs x. Theoretically such a plot should yield a straight line of slope $\frac{\gamma+1}{2\gamma\lambda}$. However, the observed data when plotted in this way had slopes which varied between 50% and 100% of that given by the theory with most results close to 70%.

G. Werth[5] conducted a similar investigation using one and one-half inch diameter pipes and a frequency range from 300 to 1200 cycles per second. His results were similar to those reported by Rudnick.

O. B. Wilson, Jr. and David Bies conducted a third and similar investigation but used an intermediate size pipe

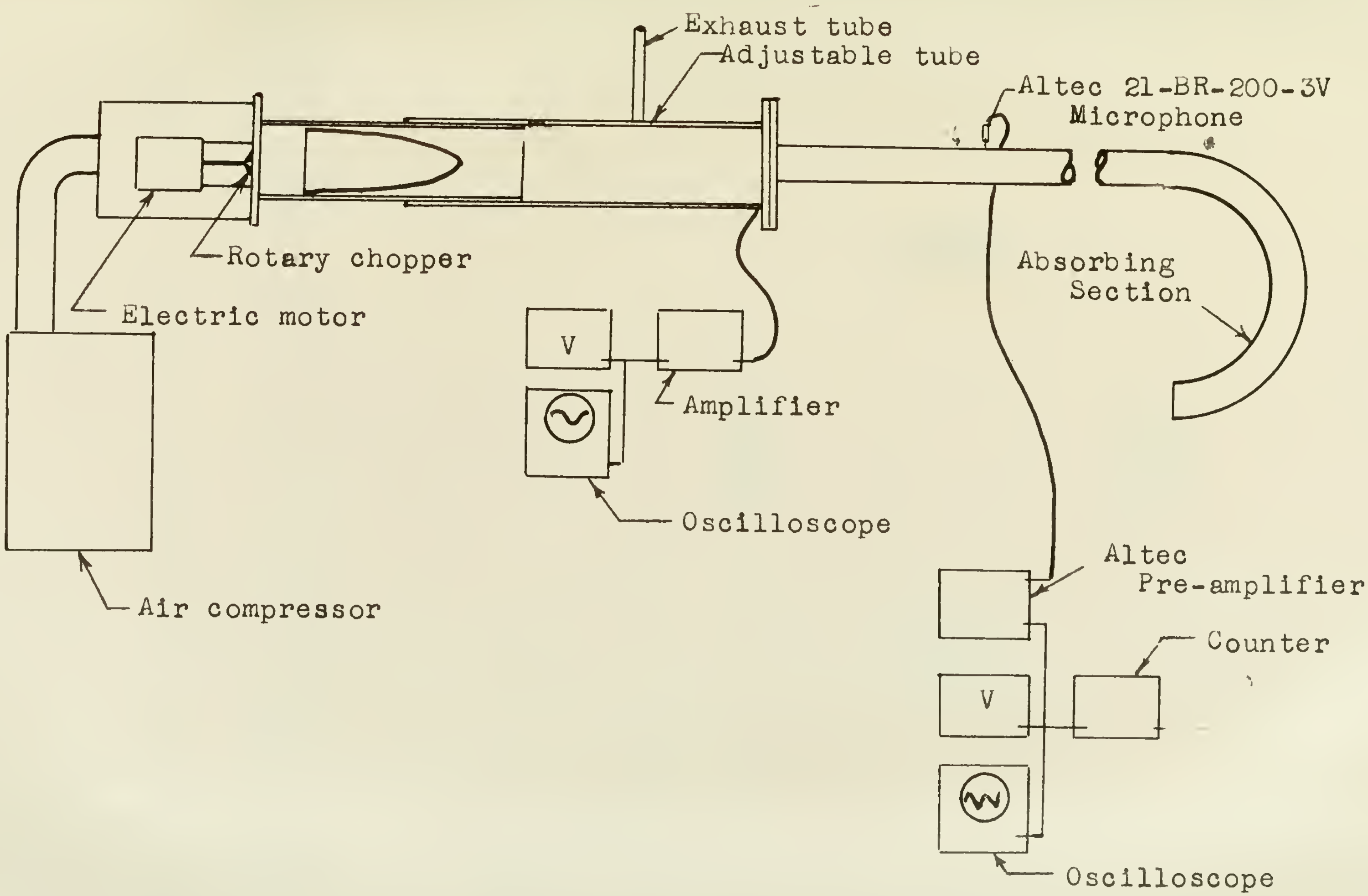
[5] Werth, op.cit.

(4 13/16" I.D.) for the purpose of determining whether the tube size influenced the observed rate of attenuation. Pressure amplitudes of the order of 0.1 atmospheres were used with frequencies ranging from 40 to 180 cycles per second. No simple dependence of attenuation on tube radius was found. [2]

5. Description of the equipment

In order to produce the high intensity sound waves that were necessary for the rapid formation of the shock waves studied, it was necessary to cut a stream of compressed air with a rotor blade. A compressor capable of delivering up to 400 cubic feet of air through a range of pressures up to ten pounds per square inch was used to feed air to the chopper (Fig 3). The compressor was originally designed for and used in testing pressurized cabins of aircraft of the U. S. Navy for leaks. In order to meet the fire regulations, the gasoline motor was removed and a 15 horsepower electric motor was mounted on the frame. This was coupled to the shaft of the compressor by a triple v-belt drive using a two to one ratio in order to approximate the rated speed for which the compressor was designed.

The chopper consisted of a plate of ½ inch aluminum with four holes cut into it. See Fig. 4. These holes were closed and opened by means of a rotor, mounted flush with the plate and driven by a 0.5 horsepower motor. When the rotating blades of the chopper were in such a position that the ports were open, the air was permitted to pass through freely producing a condensation of the air in the chamber. At a quarter turn later, the holes were closed. The momentum of the air particles carried them into the tube thus producing a rarefaction. It was this series of condensations and rarefactions that produced high intensity sound waves.



Schematic Diagram of the Equipment

Figure 3

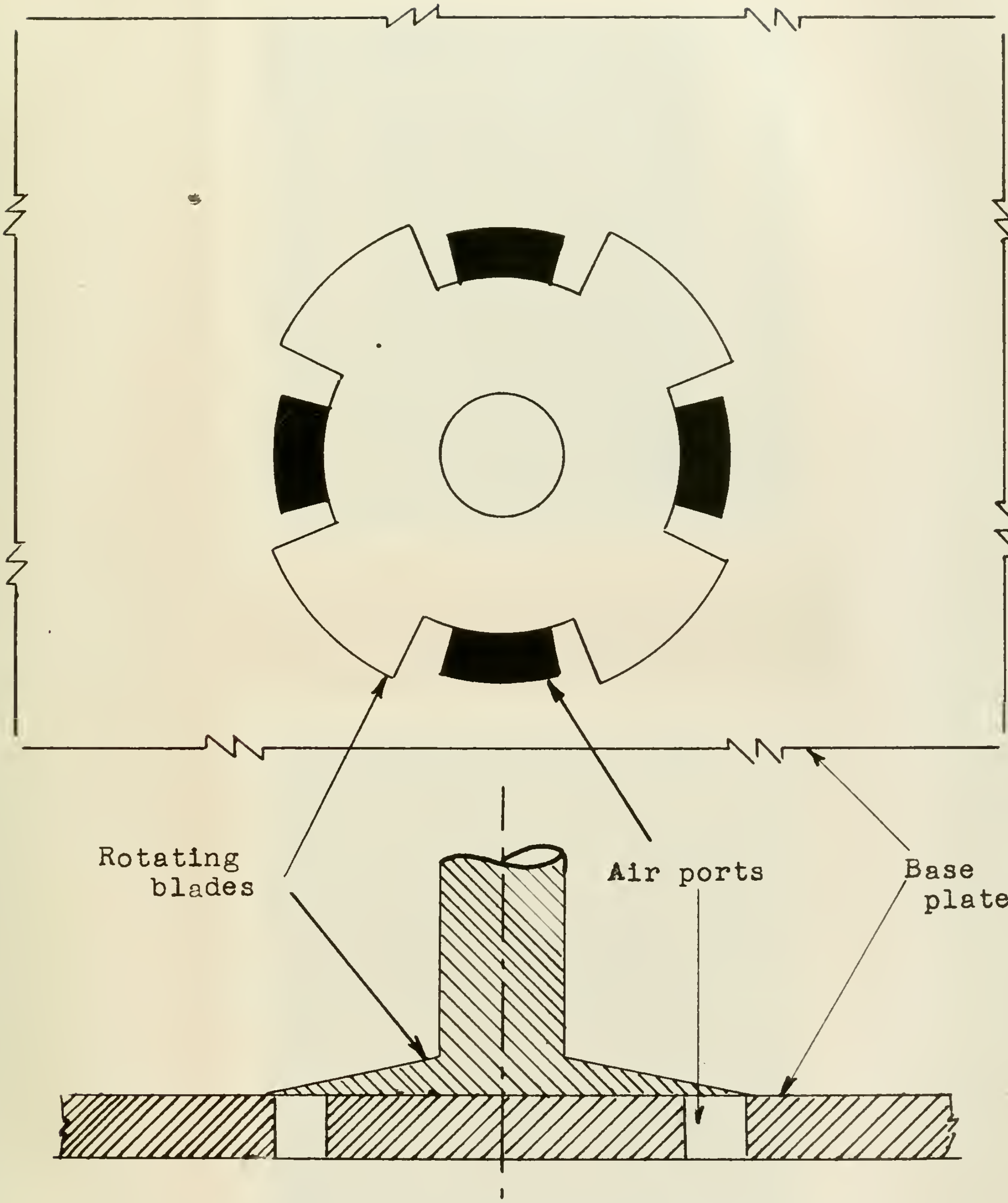


Figure 4 Schematic Diagram of the Rotary Chopper

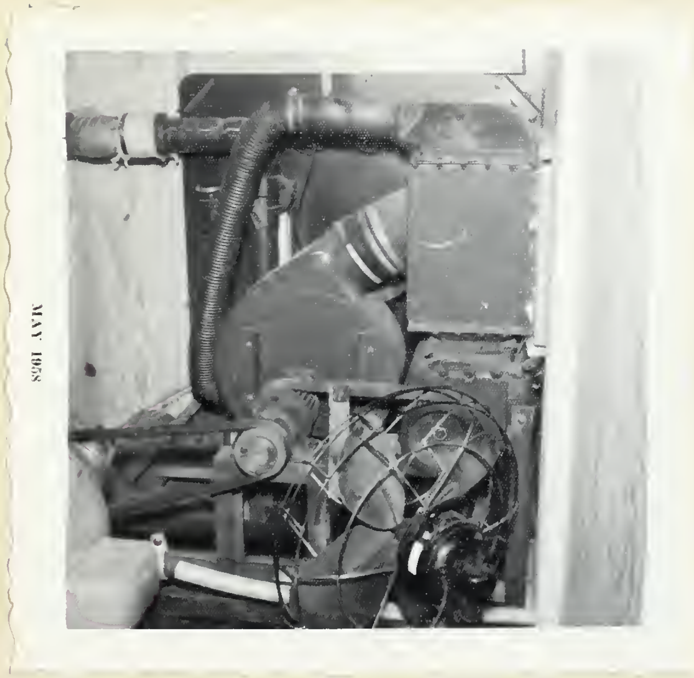


FIG 5 Air Compressor

FIG 6 Siren

FIG 7 Air Compressor and Siren before Sound Proofing

Fig 8 Air Compressor and Siren after Sound Proofing

The waves then passed into an adjustable chamber consisting of a fixed pipe five and one-half inches inside diameter over which slid another pipe six inches inside diameter. See Fig 6. An airtight fit was maintained by means of two rubber O-rings mounted on the outside of the smaller pipe. The proper adjustment of the outer pipe permitted it to be placed at a distance equal to an integral number of half wave lengths from the chopper. This assured a maximum pressure swing at the entrance to the shock tube. It was in this tube that the sound wave was to grow into a shock wave.

It was originally planned to use a barium titanate transducer mounted on the end of a long probe tube inserted into the shock tube from the end, to measure the pressure variation of the shock waves. The construction and calibration of these microphones proved to be a very difficult job. After the microphones were constructed, they proved to be too insensitive to produce a good trace on the oscilloscope. In order to overcome the weakness of the signal produced by the crystal, a system employing a doubly shielded conductor and a cathode follower preamplifier was tried. Although this increased the response, it was found that the system was microphonic and, it was felt, would yield highly distorted results.

The system finally decided upon and used to measure the pressure variations was to drill and tap holes in the side of the shock tubes at one foot intervals starting four feet from

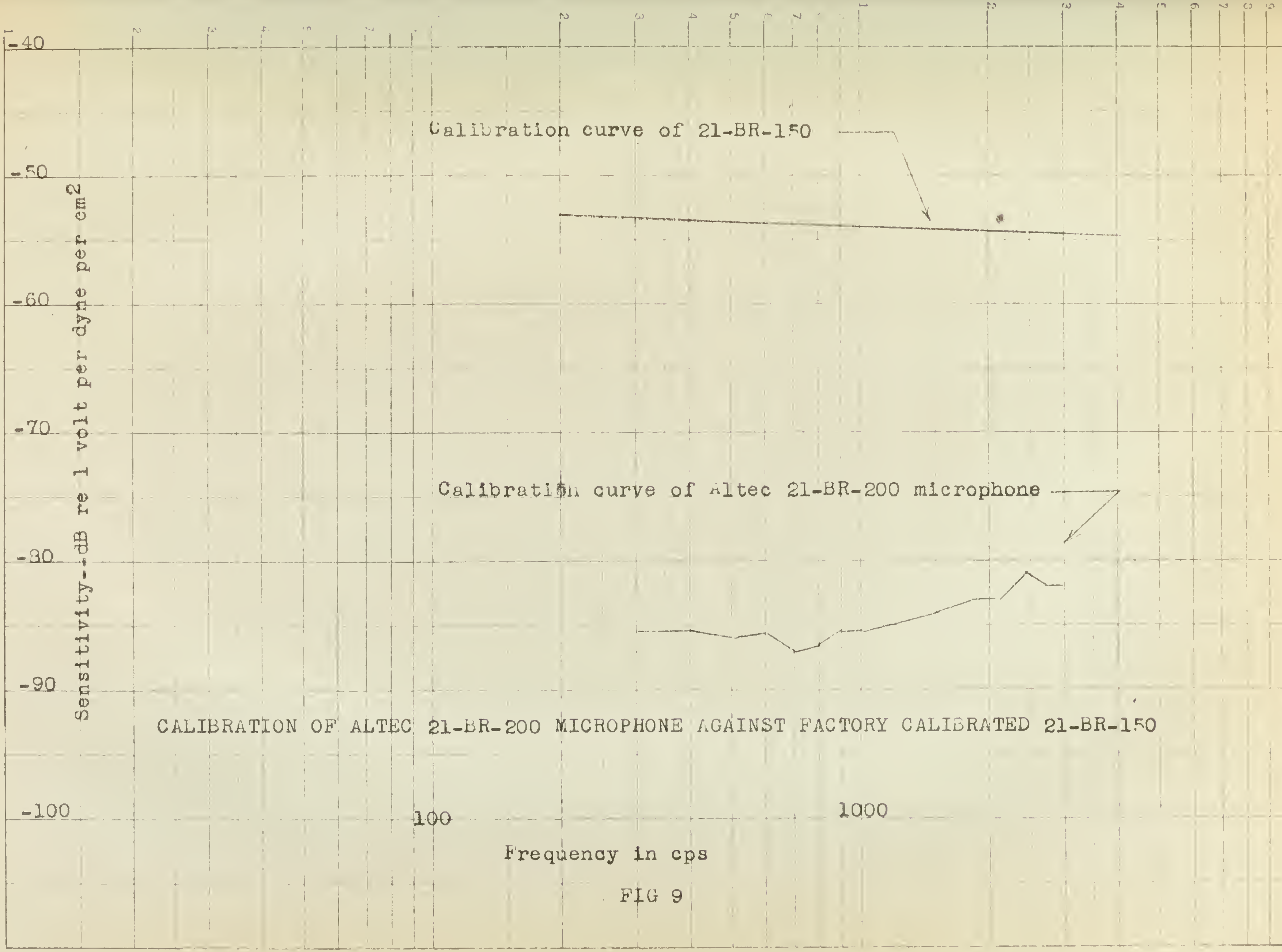
the entrance to the growth tube. An Altec 21-Br-200-3V microphone was fitted with a 1/8" x $1\frac{1}{2}$" adapting probe tube and inserted into the holes in succession. The pressure was read on a Hewlett-Packard 400 volt-meter. In parallel with the volt-meter was an oscilloscope on which could be viewed the shape of the wave and a counter in order to accurately determine the frequency of the shock waves. By reading the counter before data was taken, it was possible to eliminate any error that might have been introduced by a variation in the frequencies and a concurrent variation in intensity.

The Hewlett-Packard voltmeter is calibrated in decibels with respect to one milliwatt at 600 ohms. In order to convert this reading to decibels with respect to one volt, a correction of 2.2 decibels had to be subtracted from the meter reading (see Appendix A). The meter responds to the average rectified voltage and is calibrated in terms of the r.m.s. voltage of a sine wave. It has been determined that when a saw-tooth is fed into the meter, a correction of 11 db. must be added to give the peak-to-peak voltage change (See Appendix B).

The Altec 21-BR-200-3V microphone was calibrated against a known standard which in our case was an Altec 21-BR-150 microphone which had been calibrated by the manufacturer. The original characteristics were very poor because of the large air cushion between the probe and the

diaphram of the microphone. When a brass plug was added to the inside of the probe base, the air space was greatly reduced and the characteristics flattened out considerably, particularly in the range of frequencies at which the investigation was carried out. The calibration curve is shown in Figure 9.

The shock tubes were a series of twenty foot seamless steel tubes with inside diameters of 0.75 inch, $1\frac{1}{4}$", 1-3/4", $2\frac{1}{4}$" and 2-3/4". These were each fitted with a plate which was bolted to the plate welded on the large growth tube of the adjustable chamber. On the far end of the tubes was placed an absorption section consisting of a straight length of pipe followed by two 90° bends. These sections were filled with tapered glass wool in such a manner as to change the cross-section of the pipe gradually. In this way, the shock wave was rapidly absorbed and reflections were kept to a minimum.



CALIBRATION OF ALTEC 21-BR-200 MICROPHONE AGAINST FACTORY CALIBRATED 21-BR-150

FIG 9

6. Conduct of the investigation

This investigation was conducted on two tubes, i.e.; the 3/4" I.D. and the 1-3/4" I.D. pipes only because a fracturing of the diaphram of the 21-BR200-3V microphone caused suspension of the tests.

The speed of the chopper was controlled with a variac. The microphone was placed in each of the holes in the test pipes with the remaining holes plugged with a standard screw. Care was taken to prevent the screw from entering the tube and thereby distorting the wave form. Readings were taken on the volt-meter only after checking the electronic counter to make sure the frequency was constant.

7. Results of the investigation

From Rudnick's equation [1]

$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{\gamma+1}{2\gamma\lambda}(x - x_0)$$

it can be expected that the attenuation per foot of pipe should be frequency dependent. This is borne out by the graphs Fig. 12 and 13. If the equation is rearranged slightly we have the expression:

$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{\gamma+1}{2\gamma}\left(\frac{x - x_0}{\lambda}\right)$$

and a graph of $1/\delta$ vs x/λ should be a linear function with a constant slope of $\frac{\gamma+1}{2\gamma}$. The linearity is verified in Fig 14 and 15, however, the slopes vary with frequency. The numbers in parentheses are the value of the ratio of the observed slope to the theoretical slope. This value we have called R.

This indicated that the equation above does not adequately describe the attenuation. If the refinement used by Wilson and Bies

$$\frac{1}{\delta} - \frac{1}{\delta_0} = a_1 x + \frac{1}{\delta_{ave}} a_2 x$$

is used and values for a_1 and a_2 are substituted, we get

$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{r+1}{2r}\left(\frac{x-x_0}{\lambda}\right) + \frac{170\sqrt{f\nu'}}{dc}(x-x_0)\frac{1}{\delta_{ave}}$$

substituting $c = \lambda f$

$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{r+1}{2r}\left(\frac{x-x_0}{\lambda}\right) + \frac{170\sqrt{\nu'}}{d\sqrt{f}}\left(\frac{x-x_0}{\lambda}\right)\frac{1}{\delta_{ave}}$$

and dividing by $(x-x_0)/\lambda$

$$\frac{\frac{1}{\delta} - \frac{1}{\delta_0}}{\left(\frac{x-x_0}{\lambda}\right)} = \frac{r+1}{2r} + \frac{170\sqrt{\nu'}}{d\sqrt{f}}\frac{1}{\delta_{ave}}$$

but $\dfrac{\frac{1}{\delta} - \frac{1}{\delta_0}}{\left(\frac{x-x_0}{\lambda}\right)}$ is the observed slope of the graphs on Fig 14 and 15. If both sides of the equation be divided by $\frac{r+1}{2r}$ we have on the left side of the equation the expression that we have called R.

$$R = 1 + 1/\delta_{ave}\ \frac{170\sqrt{\nu'}}{d\sqrt{f}} \times \frac{2r}{r+1}$$

Again rearranging

$$(R-1)\sqrt{f} = \frac{1}{\delta_{ave}} \cdot \frac{170\sqrt{\nu'}}{d}\ \frac{2r}{r+1}$$

and plotting a graph of $(R - 1)\sqrt{f}$ vs $1/\delta_{ave}$ for a given gas and pipe radius a straight line with a slope of $\frac{170\sqrt{\nu'}}{.86\,d}$ should result. The experimental data does not give constant values hence one must conclude that the equation used by Wilson and Bies does not adequately describe the situation either.

From Fig 14 and 15 we see a definite variation with

frequency and comparing the slopes of similar frequencies in the two pipes, it can be seen that the waves attenuate faster in the smaller pipe.

When the ratio of observed to theoretical slopes are plotted against frequencies, (Fig 16) it is noted that as the frequencies increase, the ratio of observed to theoretical slopes decreases to a certain value of the frequency after which it rises. This would indicate that some phenomenon has been altered radically. The parallelism of the curves after the "critical" frequency is of particular interest.

Further investigation should be conducted to determine the shape of this curve more accurately and to determine whether this relation holds for other sizes of pipes.

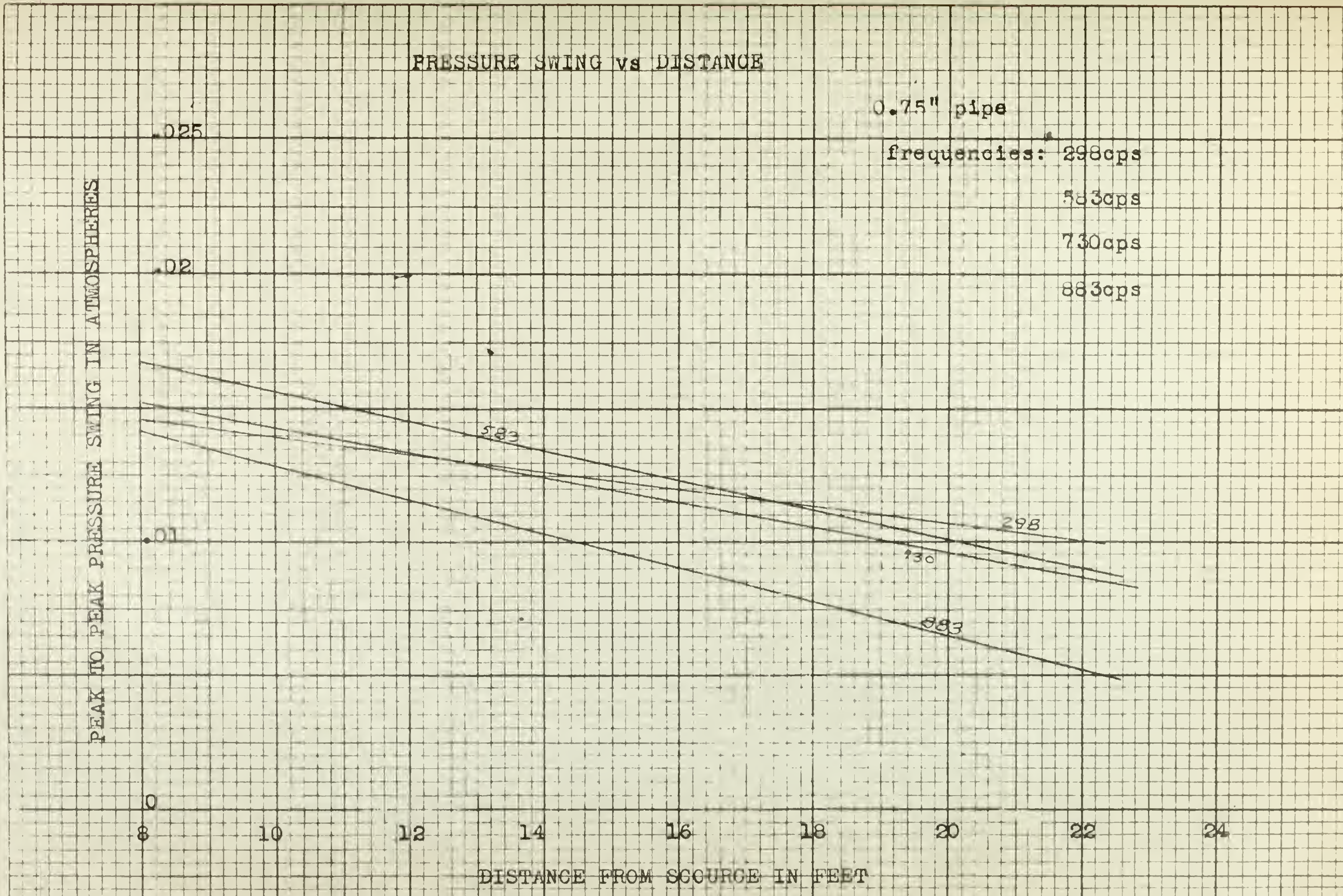

PRESSURE SWING vs DISTANCE
0.75" pipe
frequencies: 298cps
583cps
730cps
883cps
PEAK TO PEAK PRESSURE SWING IN ATMOSPHERES
.025
.02
.01
0
583
298
730
883
8
10
12
14
16
18
20
22
24
DISTANCE FROM SOURCE IN FEET

FIG 10

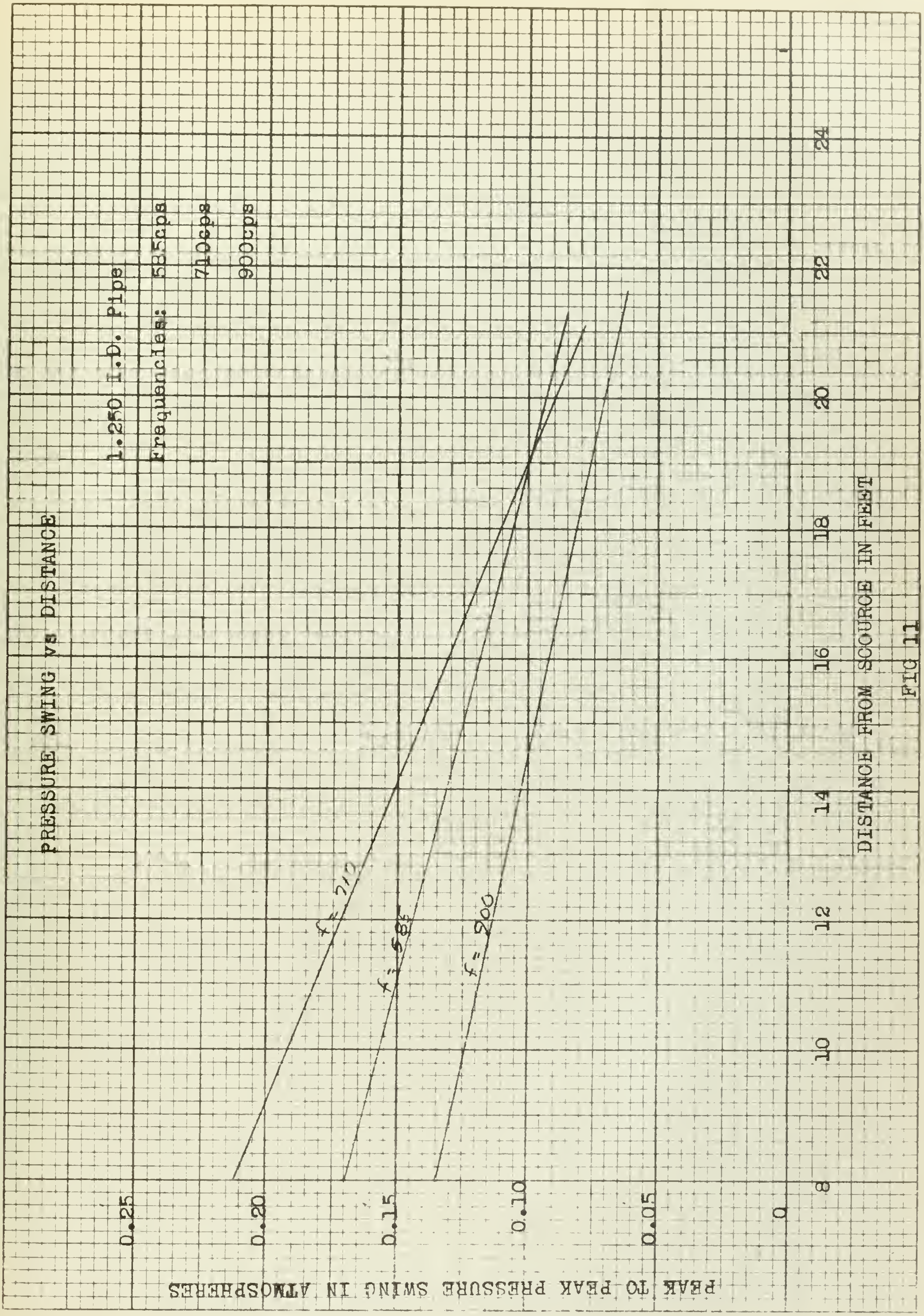

PRESSURE SWING vs DISTANCE
1.250 I.D. Pipe
Frequencies: 585cps
710cps
900cps
f = 710
f = 585
f = 900
PEAK TO PEAK PRESSURE SWING IN ATMOSPHERES
0.25
0.20
0.15
0.10
0.05
0
8
10
12
14
16
18
20
22
24
DISTANCE FROM SCOURCE IN FEET

FIG 11

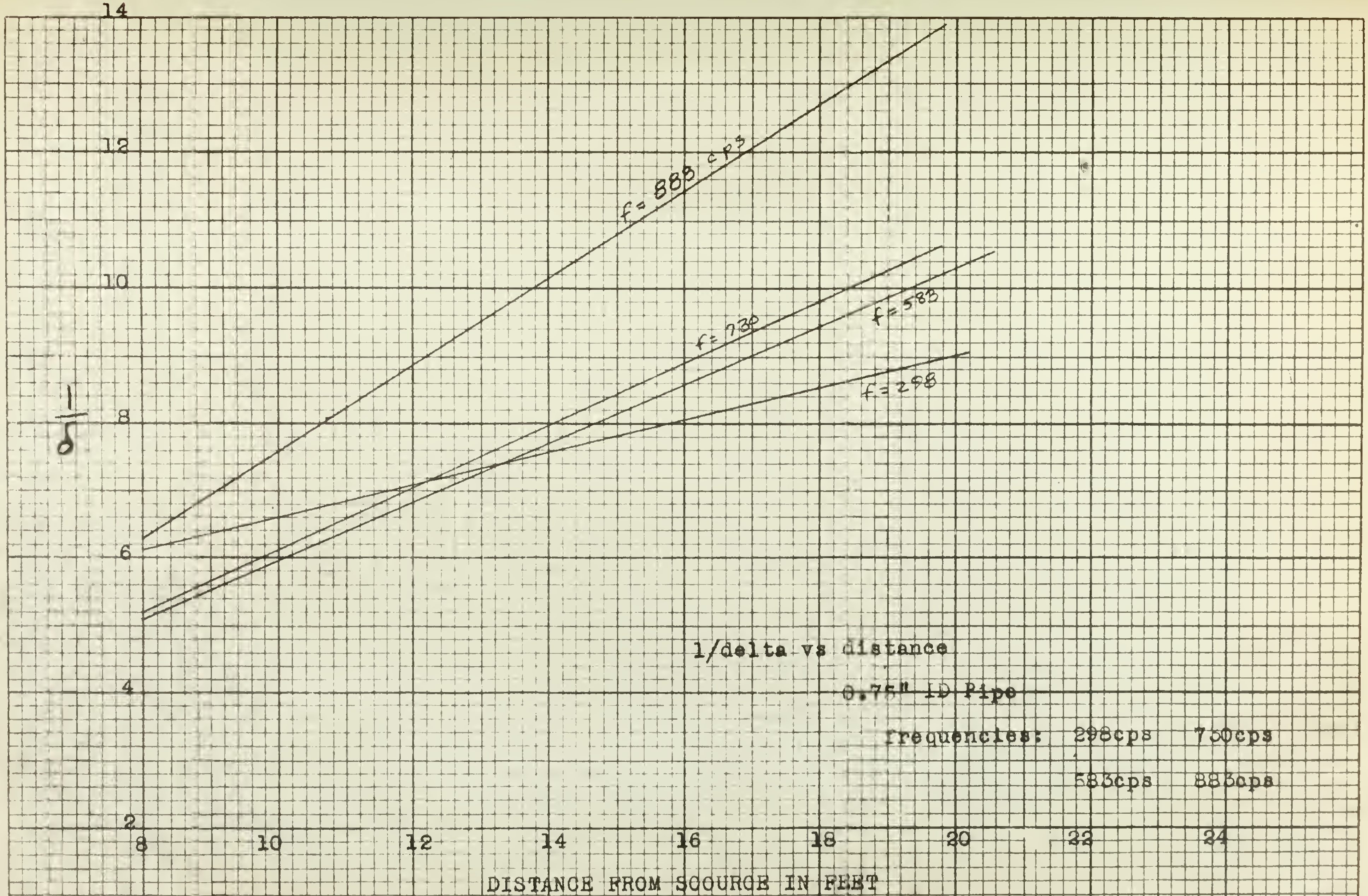

14
12
10
8
6
4
2
$\frac{1}{\delta}$
f = 883 cps
f = 730
f = 583
f = 298
1/delta vs distance
0.75" ID Pipe
frequencies: 298cps 730cps
583cps 883cps
8
10
12
14
16
18
20
22
24
DISTANCE FROM SCOURCE IN FEET

FIG 12

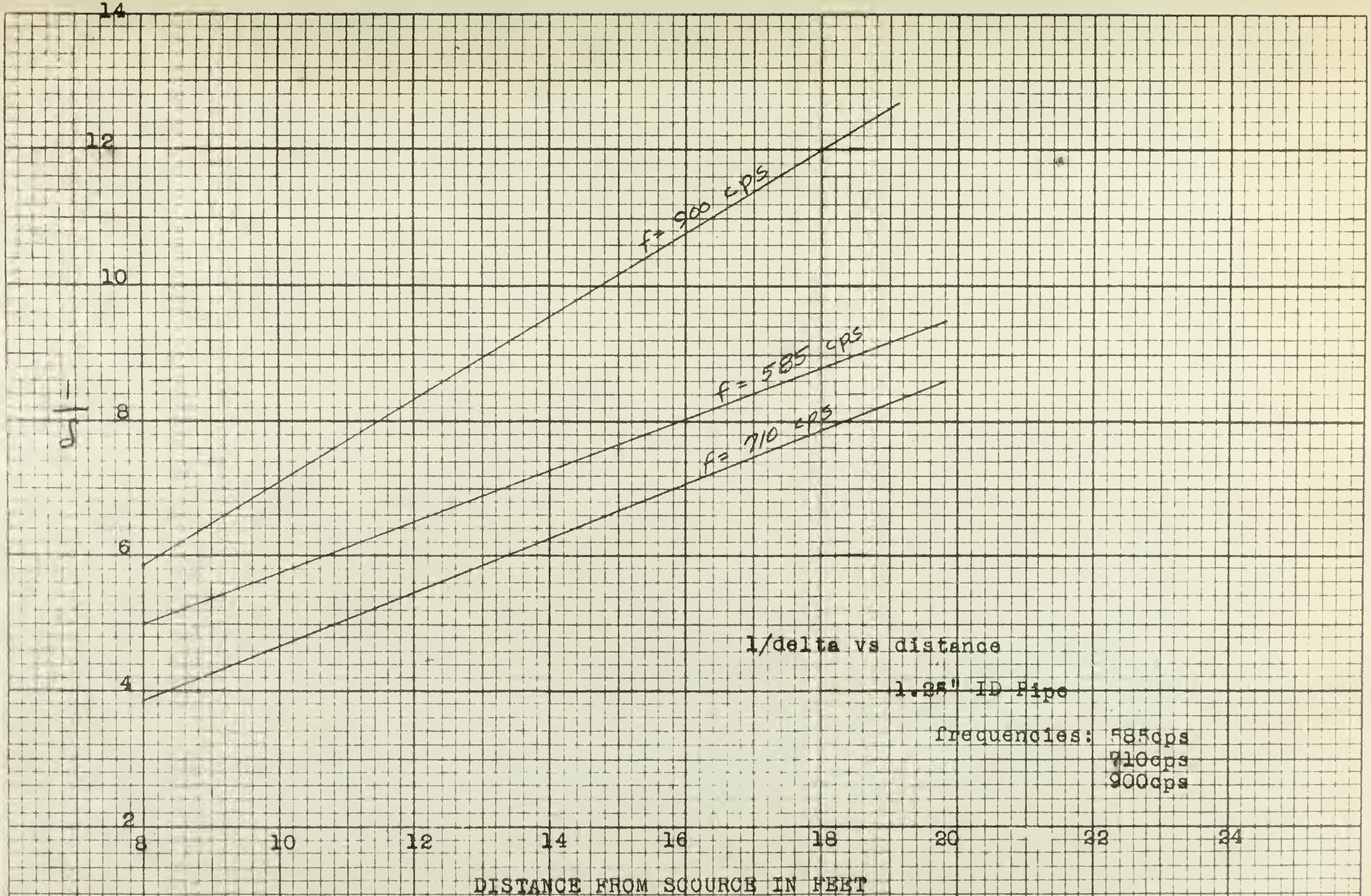

14
12
10
8
6
4
2
$\frac{1}{\delta}$
f = 900 cps
f = 585 cps
f = 710 cps
1/delta vs distance
1.25" ID Pipe
frequencies: 585cps
710cps
900cps
8
10
12
14
16
18
20
22
24
DISTANCE FROM SCOURCE IN FEET

FIG 13

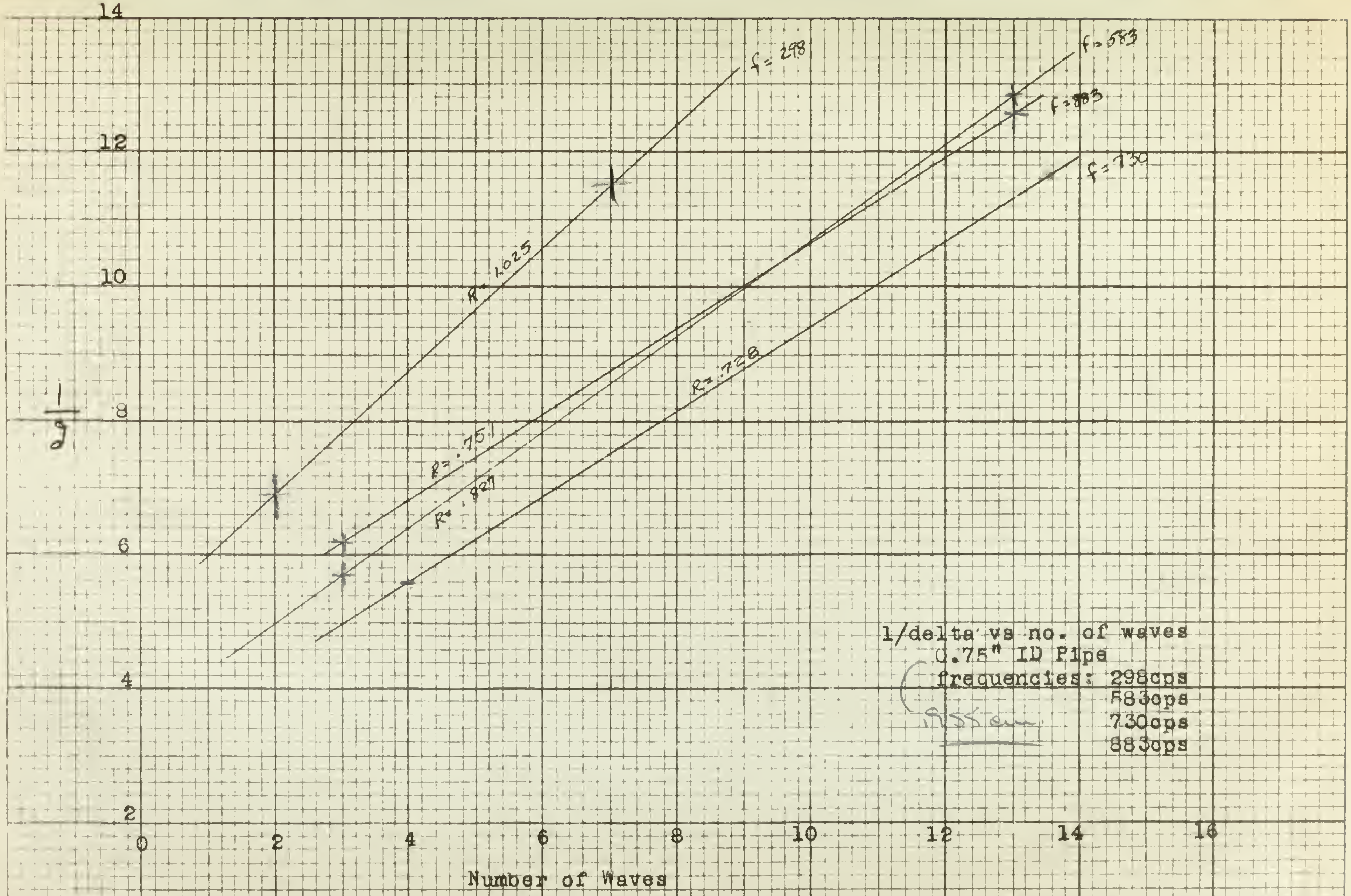

1/δ
f = 298
f = 583
f = 883
f = 730
R = .4025
R = .751
R = .827
R = .728
1/delta vs no. of waves
0.75" ID Pipe
frequencies: 298cps
583cps
730cps
883cps
Number of Waves

Fig 14

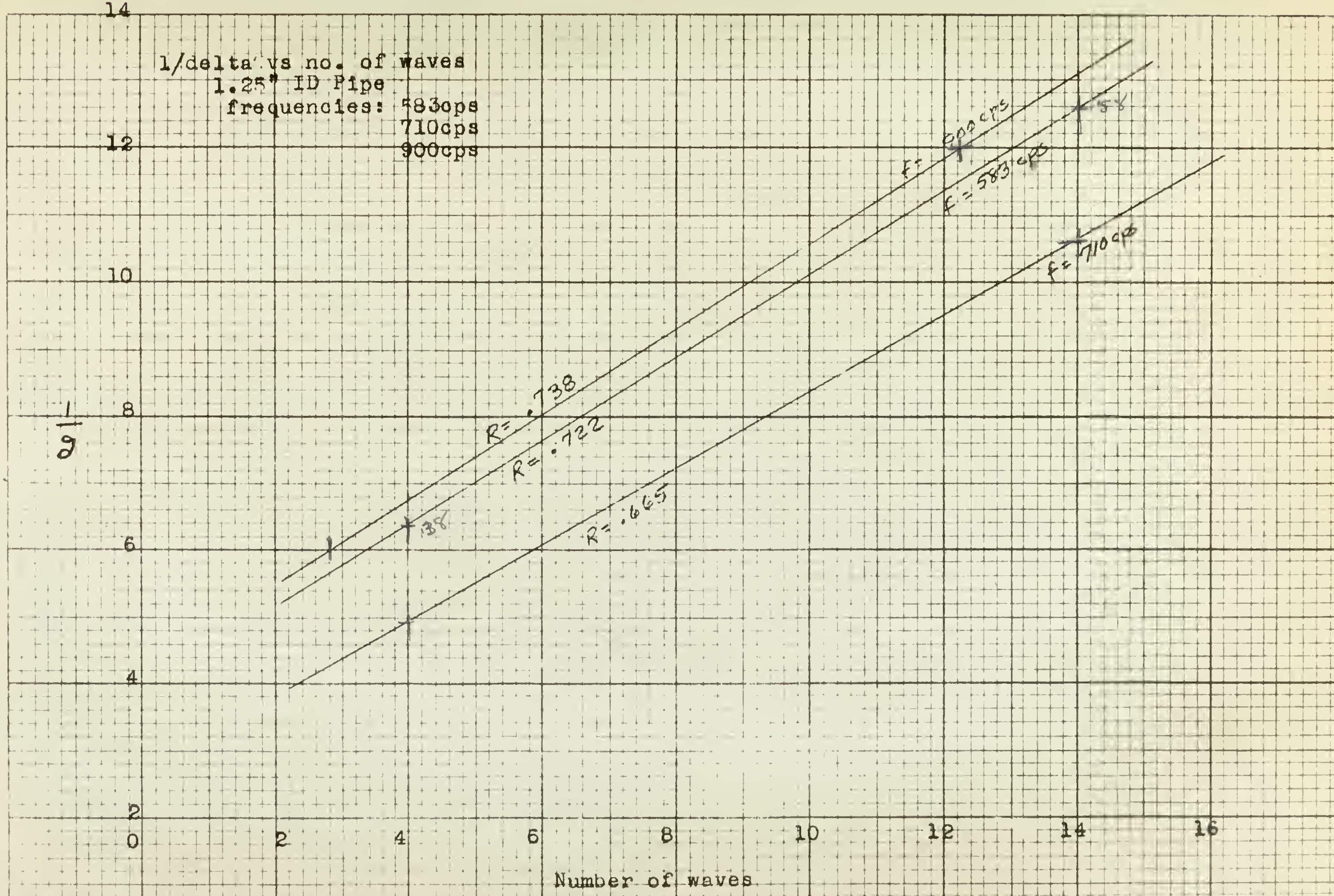

1/delta vs no. of waves
1.25" ID Pipe
frequencies: 583cps
710cps
900cps
$\frac{1}{\delta}$
14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
Number of waves
R= .738
R= .722
R= .665
f= 900cps
f= 583cps
f= 710cps

FIG 15

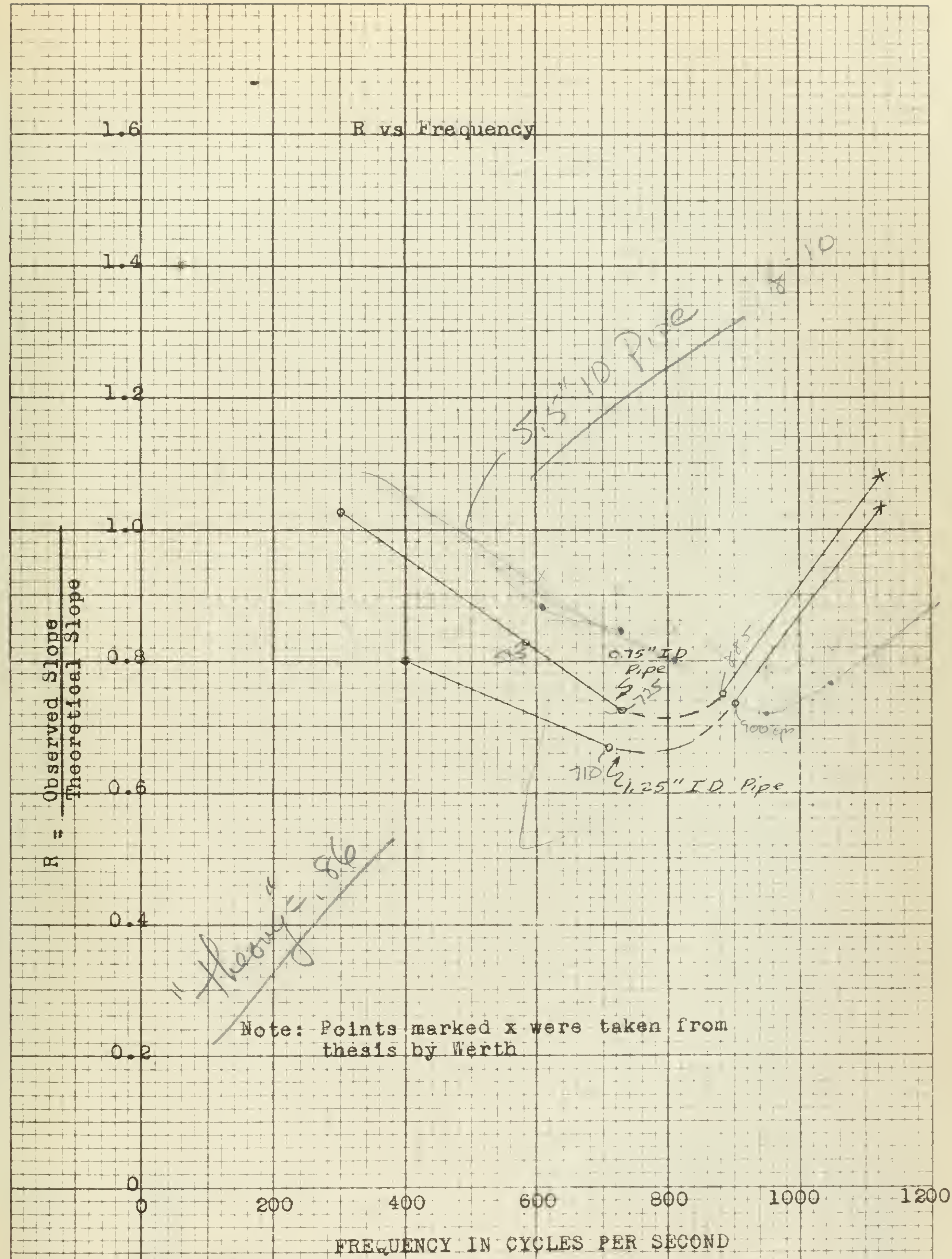

R vs Frequency
R = Observed Slope / Theoretical Slope
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
5.5" ID Pipe
0.75" ID Pipe
1.25" ID Pipe
"Theory" = .86
Note: Points marked x were taken from thesis by Werth
FREQUENCY IN CYCLES PER SECOND

FIG 16

APPENDIX A

SAMPLE CALCULATIONS

1. BR21-200-3V microphone sensitivity calibrated against factory calibrated BR21-150 microphone.

   (a) At 300 cps, BR-21-200 calibrated - 31.5 db below BR21-150.

   (b) At 300 cps, BR21-150 was factory calibrated at -54 db reference to 1 volt (rms) per dyne per cm^2 (rms).

   (c) Therefore, the BR21-200 is $-54+(-31.5) = -85.5$ db below 1 volt (rms) per dyne per cm^2 (rms)

   (d) As value in (c) above is rms, -11db additional should be included to get peak to peak values of a saw tooth wave, i.e. $-85.5 + (-11) = -95.5$db. (See appendix B)

   (e) 1 dyne per cm^2 = $+74$ db reference to 0.0002 dynes per cm^2 (=0db)

   $\therefore\ -74 - 96.5 = -170.5$ db reference to 1 volt for a 0db Sound Pressure Level (SPL) peak to peak. This is the reference number for this frequency.

   (f) As Hewlett-Packard voltmeter used reads 2.2db reference to 1 volt, $+2.2$ db must be subtracted from each reading. However, subtracting 2.2db from reference 170.5db allows use of readings directly. Therefore, corrected reference is $-170.5 + 2.2 = -168.3db_m$ on the Hewlett-Packard Voltmeter.

(Note) db_m = db's relative to voltage that gives 1 milliwatt with 600 ohms resistance.

2. At station 1 (8' from siren) for 300 cps reading on voltmeter = $+9.2\ db_m$.

   Therefore, $+9.2db - (-168.3db) = +177.5db_m$ SPL (peak to peak)

3. Using formula, $db = 20 \log \frac{P_2 - P_1}{.0002} = 177.5$ db. Solving,

   $$\frac{P_2 - P_1}{.0002} = 7.41 \times 10^8$$

   $$P_2 - P_1 = (7.41 \times 10^8)(2 \times 10^4) = 14.82 \times 10^4 \text{ dynes/cm}^2$$

   $$1 \text{ atmosphere} = 1.013 \times 10^6 \text{ dynes/cm}^2$$

   $$\therefore (P_2 - P_1) \text{ PK to Pk} = \frac{14.82\text{x}10^4}{1.013\text{x}10^6} = .1475 \text{ atmospheres}$$

4. Calculation for $\frac{1}{\partial}$, where $\partial = \frac{P_2 - P_1}{P_1}$

   $$\text{also } \frac{1}{\partial} = \frac{P_1}{P_2 - P_1} = \frac{1}{\frac{P_2 - P_1}{P_o}} - \frac{1}{2}$$

   Assuming P_o = 1 atmosphere

   $P_2 - P_1$ = pk to pk pressure of .1475 atmosphere calculated by 3 above.

   For station #1, 300 cps, 1" OD pipe

   $$\frac{1}{\partial} = \frac{1}{.1475} - \frac{1}{2} = 6.78 - .5 = 6.28$$

Note: v of sound at 20°C = 1086'/Sec

APPENDIX B

COMPUTATION FOR CONVERTING RMS VALUE OF SAW-TOOTH WAVE INTO PEAK TO PEAK VALUE

1. 1 dyne/cm^2 → -85.5 db below 1 Volt (for microphone used)

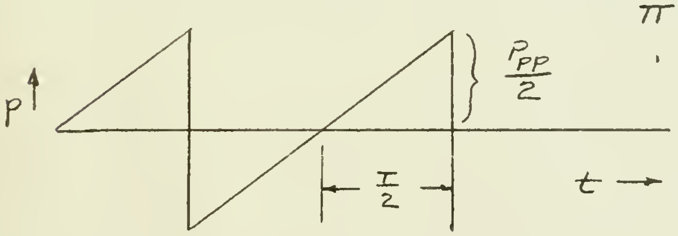
$$\frac{85.5}{20} = 4.275$$

antilog of 4.275 = 1.88×10^4

$$-85.5 \text{ db} \sim \frac{1}{1.88(10^4)} = .53 \times 10^{-4} \text{ volts} = 53\,\mu \text{ volts}$$

2. $53\,\mu$ volts $\sim$ 1 dyne/cm^2

Saw tooth wave formula, $p = \frac{P_{pp}}{\pi}\left(\sin wt - \frac{1}{2}\sin 2wt + \frac{1}{3}\sin 3wt \cdots\right)$



P_{pp} = Peak to Peak Pressure

$$P_{avg} = \frac{1}{2}\;\frac{P_{pp}/2 \cdot T/2}{\frac{T}{2}} = \frac{1}{4}\,P_{pp}$$

3. For sine wave

$$E = E_o \sin wt$$

$$\overline{E}_{avg} = \frac{2\,E_o}{\pi}$$

$$E_{rms} = \frac{E_o}{\sqrt{2}}$$

$$\frac{E_{rms}}{E_{avg}} = \frac{\pi}{2\sqrt{2}} = 1.11$$

$E_{avg} = \frac{E_{rms}}{1.11}$ (reading on voltmeter) $\simeq$ .92 db

or $E_{avg} \simeq$ 1 db less than E read on Hewlett Packard

4. From 2 above, $P_{avg} = \frac{1}{4} P_{pp}$

$$P_{pp} = 4\ P_{avg} = \frac{\text{dynes/cm}^2}{53\mu\,\text{volts}} \cdot E_{avg}$$

$$E_{avg} = \frac{E(\text{reading})}{1.11}$$

$$P_{pp} = \frac{4}{1.11}\ E\ (\text{reading}\ \frac{1}{53\text{x}10^{-6}}\ \text{dynes/cm}^2$$

$$P_{pp} = 3.6\ E\ (\text{reading})$$

and $3.6 \approx 11$ db

∴ add 11 db to rms readings to get peak-to-peak sound pressure level of saw tooth wave.

APPENDIX C

TABLE SHOWING RATIO OF OBSERVED TO THEORETICAL ATTENUATION SLOPES

1" PIPE

f cps	λ	Theoretical Slope $\left(=\frac{\gamma+1}{2\gamma}=\frac{2.4}{2.8}\right.$ for air)	Obs. Slope (from graph)	$R = \frac{Obs}{Theo}$
298	3.65	.86	.88	1.025
583	1.86	.86	.709	.827
730	1.48	.86	.625	.728
883	1.20	.86	.645	.751

1½" PIPE

f cps	λ	Theoretical Slope	Obs. Slope	R
583	1.86	.86	.622	.722
710	1.53	.86	.572	.665
900	1.20	.86	.635	.738

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